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HUMAN FACTORS IN THE DESIGN OF ELECTROLUMINESCENT DISPLAYS FOR AEROSPACE EQUIPMENT

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FOREWORD

This report was prepared by Dr. Herbert H. Stenson of the Behavior Research Laboratory, Antioch College, Yellow Springs, Ohio under Contract AF 33 (615)-1086 with the Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Major John Simons, Chief, Presentation of Information Branch, Human Engineering Division of the Behavioral Sciences Laboratory, was contract monitor. The research was performed in support of Project 7184, "Human Performance in Advanced Systems," and Task 718401, "Criteria for the Design and Arrangement of Displays."

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

This report presents an outline of a broad program of psychological research that will provide human engineering standards for the design of electroluminescent (EL) display devices. The physical characteristics of EL lighting are discussed, after which the possible types of EL displays are categorized as discrete or continuous displays, and as dynamic or static displays. Five types of perceptual tasks that might be required of an observer of an EL display are described, and each display category is then discussed in terms of the perceptual task(s) required to monitor the display in question. For each display-task combination, human factor research is proposed and some experiments are laid out in detail. The conventional variables such as intensity, contrast and viewing duration are considered for each display-task category as well as some less familiar variables based on the use of information theory. Examples of existing and proposed EL displays are given in connection with the proposed research.

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SECTION I

INTRODUCTION

In recent years advances in manufacturing technology have made possible a wide variety of electroluminescent (EL) displays. When compared with conventional displays, the use of EL displays in aerospace equipment represents significant savings in weight, space, power consumption, and maintenance. In addition, EL offers an almost unlimited variety of displays because the pattern of light output is a function of the graphic arts techniques used to design the driving electrodes. Thus, many displays that would be physically impractical using conventional display techniques can be easily constructed from EL materials.

Little is known about the psychophysical and perceptual correlates of patterned EL displays since the patterns made possible by EL normally are not used in conventional displays. This report outlines the important psychological variables that need to be considered in the design of EL aerospace equipment displays and suggests general lines of research that might be undertaken in the study of these variables. For displays that are simply the EL analog of conventional displays, one might assume that the optimal design characteristics are the same as for conventional displays. Evidence that this is not true will be cited later. For this reason, the perceptual effects of EL displays that are analogs of conventional displays are discussed in this report as well as the possible perceptual effects of new EL displays for which no conventional counterpart exists.

To acquaint the reader with the physical principles of the EL phenomenon and associated technology, a summary of these principles is provided in Section II. Following this, the standard categories of conventional aerospace equipment displays with a categorization of their EL counterparts and possible new types of EL displays are presented and discussed in Section III. In Section IV, the perceptual tasks required in the monitoring of EL displays are listed, and in Section V the human factors research required for each category of EL display is discussed.

SECTION II

PHYSICAL PRINCIPLES AND TECHNOLOGY IN ELECTROLUMINESCENT LIGHTING

PRINCIPLES AND CONSTRUCTION

Electroluminescence as a scientific phenomenon was reported prior to 1950, but was not extensively studied until after the creation of a practical EL lamp in 1950 (Payne, Mager, & Jerome, 1950). The phenomenon of EL consists of the emission of light from a phosphor placed in an alternating electrostatic field.

The reasons for the emission of light in an EL phosphor are complex and not fully understood. Several diverse theories of EL have been reviewed by Strock and Greenberg (1964). For this report it will suffice to grossly describe the process as follows. When a field is established across a layer of an EL phosphor, electrons are pulled away from certain atoms in the phosphor, leaving electron "holes". Upon the collapse of the field, electrons return to these "holes" and light emission occurs. The light emission is the radiation equivalent of the difference in energy between the "hole" and the last stopping place of the electron (Strock & Greenberg, 1964). Equivalently one may think of the phenomenon of light emission as being the result of the acceleration of electrons and their collision with certain "light centers" in a phosphor molecule.

Figure 1 shows a sketch of an edgewise view of an EL lamp. The two electrode plates (A and D) form a capacitor which, when charged, creates a field across the

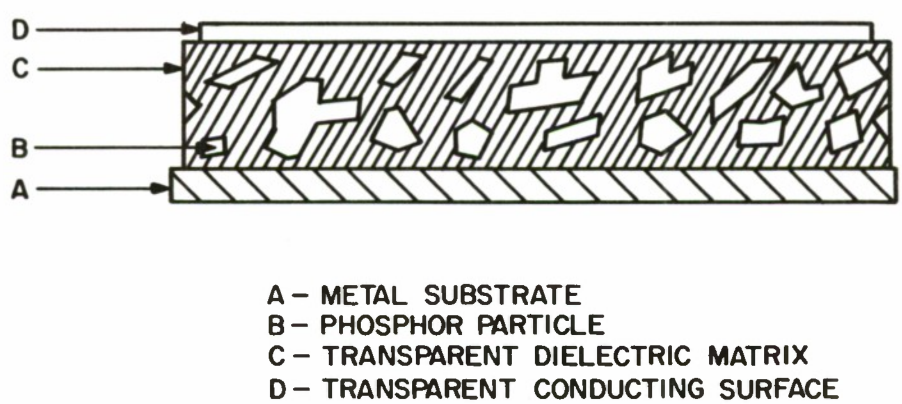

Figure 1. Construction of a Typical Electroluminescent Lamp.

phosphor embedded in the dielectric layer. If the field is created with an alternating voltage, a double-peaked pulse of light is emitted by the phosphor for each change in direction of the field potential. Thus, when an a-c source is used to create the field, two primary pulses of light are emitted during each voltage cycle. The light pulses are out of phase with the voltage and are emitted during the collapse of the field following the peak of the voltage phase that generated the field. EL with d-c activation has also been studied but is not in common use.

Since the amount of light emitted per unit time must be a function of both the amplitude and frequency of the pulses, the luminance of an EL lamp is dependent upon both the size and frequency of the applied voltage. The thickness of the dielectric layer separating the plates of the capacitor is also a factor regulating the amplitude of the pulses because the strength of the field between the plates is a decreasing function of the distance between the plates. In typical commercially produced EL lamps, the EL dielectric layer is a few thousandths of an inch thick. The relationship of light output to voltage and frequency in this type lamp is shown in Figure 2.

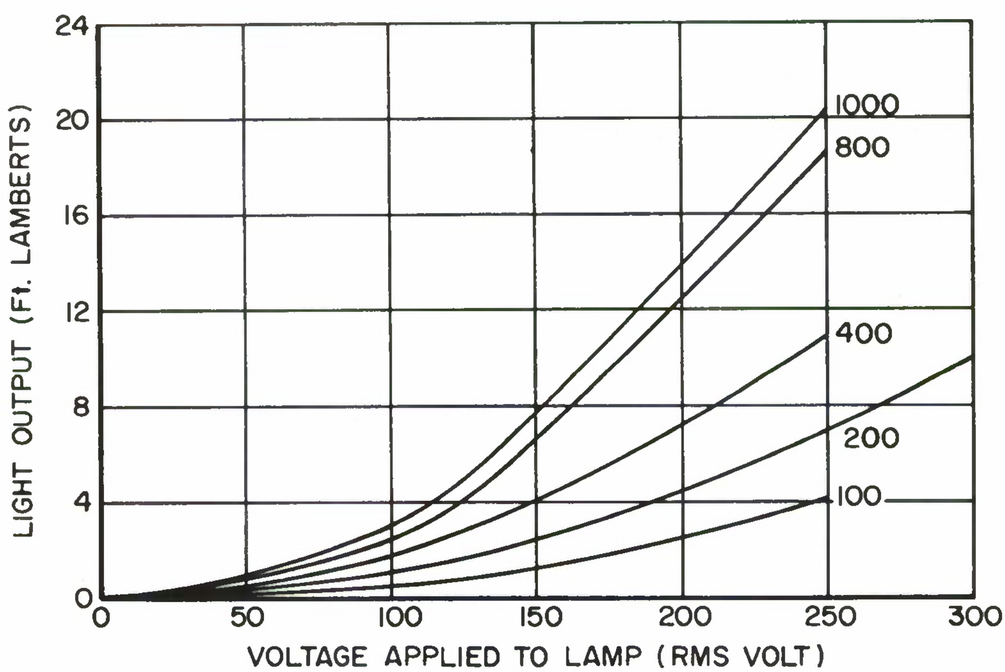

Figure 2. Variation of Panelescent Lamp Luminance with Voltage at Varying Frequencies (Courtesy of Sylvania Electric Products, Inc.).

Various types of EL lamps are available. The principal differences among them are in the phosphors and the materials from which the electrode and dielectric layers are made, with consequent limitations on the minimum thickness of the layers. A so-called flexible-plastic lamp may be made by using an aluminum foil electrode coated with a thin layer of an organic dielectric in which is embedded an EL phosphor. The unit is covered with a flexible coating of a light transmissive conductor. This entire assemblage is then placed between two flexible sheets of plastic. A rigid lamp is made by using a ceramic dielectric containing an EL phosphor, one metal electrode plate, and a sheet of glass coated with a light transmissive conductor for the other electrode.

OPERATING CHARACTERISTICS

An EL lamp does not normally maintain a constant light output over its lifetime and then instantaneously fail. Rather, it continually loses brightness over time until it becomes too dim for service. This is excellent for uses where the sudden failure of a lamp would be catastrophic. On the other hand, a lamp whose luminance is constantly changing may be undesirable for some other applications. Fortunately, compromises between these two extremes can be achieved with EL lamps. By continually increasing the voltage applied to an EL lamp, the normal decay in luminance due to aging can be partially or completely counteracted. Figure 3 shows the light output of a green-phosphor EL lamp as a function of time in use for the frequencies and voltages indicated on the individual curves. The decay function shown with a dashed line is that resulting from exactly compensating for losses in light output due to time in use by gains in output due to continually increasing the applied voltage.

The number of activations by itself has no effect on the life of an EL lamp (Fraizer, 1958). Thus, if a lamp with the decay characteristic shown by the dashed line in Figure 3 were in use 25% of the time, its life expectancy would be about 5 months with a constant luminance of 150 ft.-L. At lower intensities the life would, of course, be prolonged. The decay of EL lamps is thought to be a result of oxygen entering the dielectric layer and causing the phosphor to break down (Fraizer, 1958). More efficient ways of removing oxygen in the manufacture of EL lamps and excluding it during use are presently being developed.

The most efficient EL phosphor presently available emits green light at low frequencies and shifts toward blue as frequency is increased. Yellow and white emitting phosphors are also available but are much less efficient in light output. Red light can be efficiently produced only by converting the light energy from a green, yellow, or blue EL phosphor to red after its emission, through the use of a front-plate containing a red phosphorescent material (Strock & Greenberg, 1964). The spectral energy distribution for a typical green emitting EL phosphor is shown in Figure 4. A noteworthy feature of this distribution is that it is roughly the same as the spectral sensitivity curve for human photophic vision.

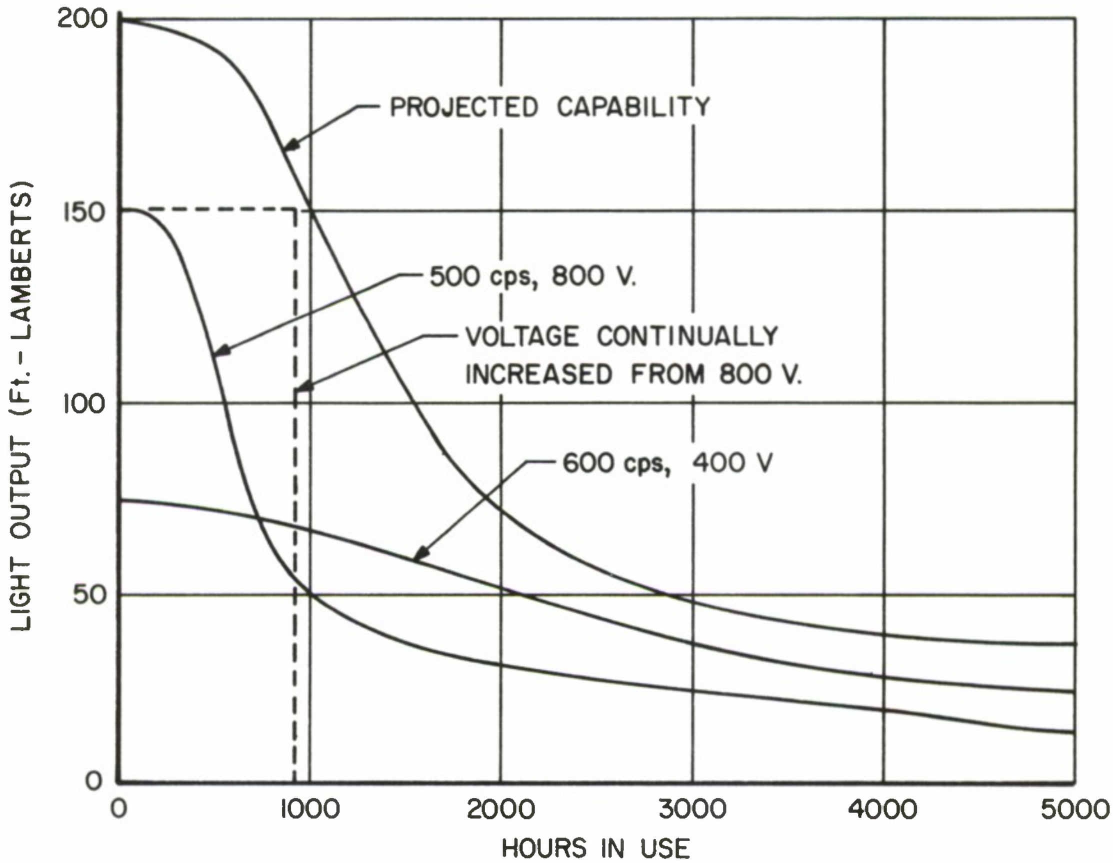

Figure 3. Luminace of High-Quality, Green-Phosphor Lamps as a Function of Time in Use at Room Temperature.

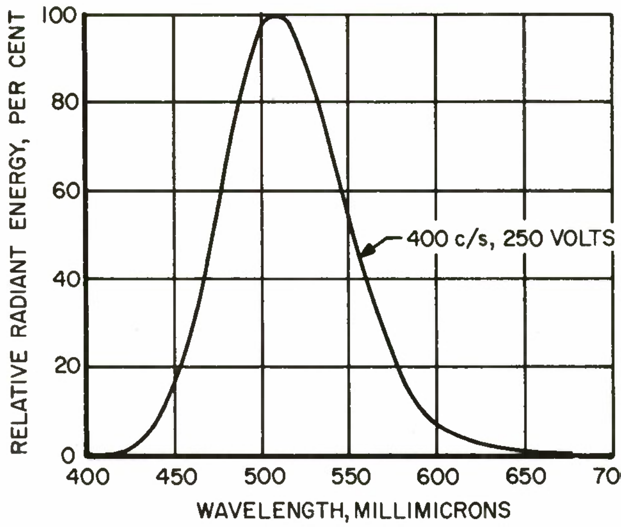

Figure 4. Typical Spectral Energy Emission Characteristics for Green Electroluminescent Phosphor (Courtesy of Sylvania Electric Products, Inc.).

Power requirements for EL lamps are generally low but vary with the size of the lamp. For the display application discussed in this report the power required does not exceed about 1 watt. Lamp efficiency is a joint function of frequency, voltage, and lamp life so that no general comparison of EL with other light sources is possible. Typical 400-cycle, 250-volt EL lamps generate about 14 lumens of light per watt, while 6-volt incandescent lamps for aircraft generate about 5 lumens of light per watt.

Another desirable feature of EL light from the viewpoint of the human engineer is that the rise and decay times are negligible. The rise time is on the order of two to three cycles and the decay time is even smaller, approaching zero.

EL DISPLAY DEVICES

Since the emission of light in an EL phosphor requires the establishment of a field across the phosphor, light will be emitted in an EL lamp only where a capacitor is formed by two electrode plates. This provides a basis for a virtually unlimited number of EL display applications, because if one of the two electrodes is constructed in a desired pattern,

light will be emitted only where the patterned electrode and the other electrode form a capacitor. If several patterns are formed and the electrodes comprising them are separated and can be individually activated, a multi-pattern display device can be constructed on a single substrate. In practice such devices are manufactured on a glass substrate, where the top electrode is patterned and the light output is seen through the transparent bottom electrode. Figure 5 is a sketch of a 14-segment alphanumeric pattern commonly used. Each segment can be activated independently, and the various combination of activated segments will produce all the alphanumeric characters.

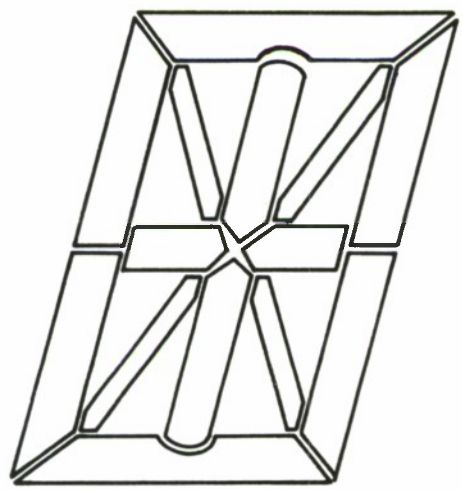

Figure 5. Schematic Drawing of a Fourteen-Segment Alphanumeric Display.

An El grid, sometimes called an XY panel, can be made by using two sets of parallel conductors placed at right angles to each other and separated by the EL dielectric layer. When an alternating voltage is applied across an X and a Y electrode, light is emitted at the corresponding XY intersect. The elements lying along each driven electrode will receive about half of the supply voltage because of the capacitive coupling between elements. Consequently, some light will be emitted along the entire length of each driven line. The light output at the intersect will be in a ratio of 10 to 1 to the light output along each driven line (Strock & Greenberg, 1964). This "cross effect" is useful for XY displays where the user needs coordinate information. In displays where only the intersect is required and the cross effect is undesirable, the light emission along each line can be suppressed either by adding a nonlinear resistive layer to the crossed grid in series

with each EL element, or by structuring the drive signals so as to have 1/3 voltage at all "off" elements and full voltage at the intersect.

Other displays in current use are (1) the bar-graph or histogram display in which each bar of light can be lengthened or shortened by the successive activation or deactivation of thin parallel electrodes placed in a sequence along the length of each bar, (2) random-access displays with individually controlled EL lamps on a single substrate having various shapes and sizes to represent the status of parts of a system, (3) polar-coordinate displays employing electrodes patterned in radial lines and concentric circles giving a radar-type display and (4) various logic and information-storage devices utilizing combinations of photoconductive, ferroelectric and silicon rectifying devices, and EL lamps and displays.

ADVANTAGES AND DISADVANTAGES OF EL DISPLAYS

Probably the two most important advantages of EL displays are their reliability and versatility. Since EL displays are solid state devices employing no filaments or vacuum and are not normally subject to catastrophic failure, their reliability is high and their life can be predetermined in great measure by the user as a function of light output requirements. The versatility of EL displays is restricted only by the imagination of the designer and the limitations of the graphic-arts techniques used to fashion the segmented electrodes.

In addition, EL displays are compact because they are flat devices. Their flatness permits in-plane presentation of information, and thus eliminates problems of parallax. Power requirements are low; voltage and frequency requirements are flexible; and rise and decay times are short.

A major disadvantage in EL displays has been that the phosphor layer from which the light for the display pattern is emitted is also a highly reflective surface. Thus, when a pattern of light is being transmitted from this layer, ambient light is also reflected from the entire layer, thereby decreasing the figure-ground contrast. This disadvantage has been overcome by the development of a nonreflective glass panel for the front of EL displays. This plate will scatter or absorb 98% of the incident ambient light, which makes the display appear as a lighted figure on a flat-black background. Further reductions in reflectance are anticipated (Peterson & Smith, 1965).

SECTION III

CATEGORIES OF CONVENTIONAL AND ELECTROLUMINESCENT DISPLAYS FOR AEROSPACE VEHICLES

Since the conceptual design of a display determines the type of perceptual behavior required in obtaining information from it, it is useful to categorize EL display systems in terms of design. One approach to this problem is to translate the currently used conceptual categories for conventional displays into categories appropriate to their EL counterparts and then to add new categories which become possible with EL displays.

CATEGORIZATION OF CONVENTIONAL DISPLAYS

Following is a convenient categorization of conventional displays from MIL-STD-803A-1 (USAF) (1964):

I. Transilluminated Indicators

   A. Single and multiple legend lights presenting information in alphanumeric form.
   B. Simple indicator lights -- pilot, bull's eye, and jewel lamps.
   C. Transilluminated panel assemblies which present whole patterns of information

II. Mechanical Scale Indicators

   A. Moving pointer, fixed scale: circular, curved (arc), horizontal straight, vertical straight.
   B. Fixed pointer, moving scale: circular, curved (arc), horizontal straight, vertical straight.

III. Other Mechanical Displays

   A. Direct-reading counters
   B. Printers
   C. Plotters
   D. Flags

IV. CRT Displays

Assuming that these categories can account for the majority of aerospace vehicle displays currently in use, we may now see how their counterparts in EL display could be classified.

CATEGORIZATION OF EL DISPLAYS

The EL displays of concern here are solid-state devices, so the distinction made above between transilluminated indicators and mechanical indicators no longer applies. All solid-state EL displays are, in a sense, transilluminated displays. An alternative broad categorization encompassing most of the conventional displays is "static vs dynamic". Included among "dynamic" displays are those capable of a continuous change of state, such as direct-reading counters. Many new displays are possible through the use of EL, most of which would correspond to category I-C above. The following categorization, then, will be the basis for discussing human factors in EL display design.

I. Static Displays

- A. Single and multiple legend lights presenting information in alphanumeric form
- B. Indicator lights -- the EL counterpart of pilot, bull's-eye and jewel lamps, on-off and flashing warning lights
- C. New static displays

II. Dynamic Displays

- A. Discrete-change displays
  1. Direct-reading counters
  2. Printers (EL counterpart)
  3. New discrete-change displays
- B. Continuous-change displays (EL counterpart)
  1. Scale Indicators
     - a. Moving pointer, fixed scale: circular, curved (arc), horizontal straight, vertical straight
     - b. Fixed pointer, moving scale: circular, curved(arc), horizontal straight, vertical straight
  2. Plotters -- X-Y and polar coordinate
  3. New continuous-change displays

These categories are necessarily somewhat arbitrary, but they will be useful guides in discussing human factors research with EL displays. "Continuous-change" EL displays, for example, must be physically designed so that change takes place in small, rapidly-presented, discrete steps, but psychologically such a display may be considered to be showing continuous change. A "static" display, on the other hand, is never completely

static. A legend light, for example, is On when its system is in operation and Off when it is not. From a psychological point of view, however, the legend light is always in a single state during the period that a human operator has any concern with it. Also, displays that can exhibit only a single change of state during system operation have been classified as static. For example, a warning light that is either Off or flashes at a constant rate has been called a static display, for the observer needs only to note presence or absence without regard to dynamics within either of those states.

SECTION IV

PERCEPTUAL TASKS IN THE MONITORING OF VISUAL DISPLAYS

To study the human factors involved in each of the EL display types given in Section III, one must first determine the nature of the perceptual tasks required of the observer. Fitts (1951) has divided all visual perception tasks into two kinds: (1) visibility tasks, where the observer is given all the time he needs to respond to a display and accuracy is the only consideration, and (2) legibility tasks, where both time and accuracy are important. Since the minimization of perception time and the maximization of perceptual accuracy is usually the goal in the design of aerospace instruments, only legibility tasks are considered here.

Hake (1957) has provided a categorization of perceptual tasks with regard to the nature of the decision required of the observer. These categories can be considered as subcategories of legibility tasks. Hake's categories of tasks are:

1. Detectability tasks. The observer's only concern is the presence or absence of stimulation without regard to its pattern.

2. Discrimination tasks. The observer must judge whether a particular stimulus pattern is the same or different than some other pattern or set of patterns.

3. Identification tasks. The observer judges the nature of the stimulus in an absolute sense.

4. Recognition tasks. The observer must decide if the stimulus is familiar; that is, whether he has seen such a stimulus before.

5. Judgmental tasks. The observer is required to assign some scale value or meaning to a presented stimulus pattern, e. g., size, location, brightness, direction, etc.

Generally, each task type in this list has the preceding task types in the list as a prerequisite. One cannot absolutely identify a signal without first being able to detect its presence and discriminate it from other signals. Likewise, one cannot decide whether or not a signal is familiar without first detecting its presence, discriminating it from other signals, and identifying it in an absolute sense. An exception to this rule is judgmental tasks. Here the kind of prerequisites demanded will vary with the type of judgment required. For example, if an observer is required to judge the absolute or relative brightness of a signal light, he need only detect the signal and discriminate it from other possible signals before making a judgment of brightness.

However, if he must judge, say, the distance to an object in space, he first must detect its presence and discriminate it from other objects. Then assuming a lack of environmental depth cues, he must identify and recognize the object in order to judge the distance, for the only cue to distance will be the apparent size of the object relative to its known size.

SECTION V

HUMAN FACTORS RESEARCH PROBLEMS IN ELECTROLUMINESCENT DISPLAY DESIGN

The perceptual tasks discussed in Section IV in combination with the categories of EL displays outlined in Section III is the basis for the following discussion of human factors research problems in EL display design. The new displays that are made possible by the use of EL are of considerable interest and will be discussed at greater length than the EL counterparts of conventional displays.

INTERACTING VARIABLES

Three important interacting variables that need to be studied for all categories of EL display are display intensity, display contrast, and the state of light or dark adaptation in the observer. Because the life of an EL display depends largely on the intensity at which the display is run (see Section II), the displays should be run at the lowest intensity compatible with the perceptual task required. Thus, the lower limit of display luminance should be determined for any display, with regard to observer's task.

Interacting with intensity is the minimum figure-ground contrast ratio required in a display for adequate performance of the perceptual task. If a low-reflective frontpiece is used on the display, then only a small percent of the ambient light will be reflected from the display. Since displays must be designed to be read under conditions where ambient illumination can vary anywhere from essentially zero to well over 10,000 foot-candles this small percent will not always be negligible. Therefore, the minimum figure-ground contrast needed for the perceptual task must be found for the upper and lower limits of expected ambient illumination.

The state of visual adaptation of the observer interacts with the brightness and contrast of the display. Although normally the state of adaptation is highly correlated with the current level of ambient illumination, adaptation should be experimentally varied, independent of ambient illumination and display intensity, to test the effects of certain rare, real-life situations such as temporary flash blindness.

The remainder of this paper is a discussion of psychological variables specific to each EL display category. It should be noted that brightness, contrast, and visual adaptation interact not only with each other but with these specific variables.

STATIC DISPLAYS

Legend Lights. The task required of an observer in reading legend lights is one of absolute identification, which assumes detection and discrimination. Previous human factors research on the identification of alphanumeric legends, applicable to conventional displays, cannot be unqualifiedly used as a guideline for EL display design because EL displays have some unusual display characteristics. Normally, the alphanumerics used in EL displays are lighted characters seen on a greenish-white background or on a nearly black background if a low-reflective frontpiece is used on the display, and the spectral energy distribution of the light is not the same as that from an incandescent source. Thus, past research covering the relevant variables for identification of transilluminated alphanumerics using conventional lamps and various painted backgrounds may not be applicable to EL displays unless the spectral energy distribution and luminance level of the displays used were approximately the same as EL displays.

It is known (see Hake, 1957), that interactions exist in pattern perception between psychological pattern complexity, degree of figure-ground contrast, absolute intensity, and duration of viewing. For example, discrimination between complex patterns requires a longer duration of viewing than discrimination between simple patterns. Complexity, then, can be traded for speed of discrimination. Similarly, display intensity or area can be traded for viewing duration in a detection task. It therefore would be appropriate to study the percent correct identifications of EL legends as a joint function of complexity, contrast, intensity, and viewing duration. The last three of these four variables can be physically defined in the conventional manner, but the complexity of a display can not be easily defined. Some of the obvious variables involved in the complexity of alphanumeric legends are character style, stroke width, height-width proportions, and character spacing. These variables have all previously been related to the readability of dark alphanumerics on a light background and light alphanumerics on a dark background (Berger, 1944; Brown, Lowery & Willis, 1951; Brown & Lowery, 1949; Holmes, 1931; Soor, 1955; Taylor, 1934). The readability of EL alphanumerics, however, may not bear the same relationship to these variables as the conventional displays used in these studies. A fairly restricted study of EL displays by McLean and Miller (1965) indicates this; thus, for EL displays, these variables should be re-examined.

However, display complexity involves more than the simple physical characteristics of the alphanumeric characters. The gestalt formed by the display is a determinant of its psychological complexity, and the nature and size of the array of displays in which a given display is embedded also affects the accuracy of identification. For studying both of these aspects of display complexity, information theory seems to be a natural tool. Tables exist (Shannon, 1951) giving the information content of the English alphabet and of sequences of letters of the alphabet, and Hyman (1953) shows that reaction time to a display is an increasing linear function of the number of bits of information in the display. Garner (1962)

shows that "total information" may be analyzed into "between" and "within" components in a manner directly analogous to analysis of variance. Thus, for fixed levels of contrast, intensity and character styles, reaction time, and correctness of identification can be obtained for various combinations of "within display" information and "between display" information.

Indicator Lights. The versatility of EL displays makes possible the incorporation of most indicators into other displays that show data from the same system for which the indicators are intended. This design change results in displays that are more psychologically and physically economical (see discussion under New Static Displays). However, there are some systems for which an indicator alone is all that is required.

The observer of this type of display is required to detect a single change of state. With EL indicators the change might take such forms as a change in intensity or a change from a constant state to a flashing state. A basic research program on the detection of EL indicators should include the study of five types of detection: (1) the detection of the onset of a previously unlit indicator, (2) the detection of the offset of a previously lit indicator, (3) the detection of a change from unlit to flashing, (4) the detection of a change from constantly lit to flashing, and (5) the detection of increments in luminance in a constantly lit indicator.

The relevant variables for all five types of detection are the intensity, contrast, shape, and area of the indicator. When a flashing light is used the flash rate is a relevant variable, and when detection of increments in luminance is being studied the increment size is a relevant variable. A binary response such as "Yes" or "No" is required of an observer in a detection experiment, and a summary measure such as "percent detected" is then related to the physical variables. In experiments of this type the exposure duration of the stimulus must also be a variable. However, reaction time to the change of state might also be the criterion measure, thus eliminating the need for control of exposure duration.

Once a change of state in an indicator is detected, the change must be located and interpreted when the indicator is embedded in a display complex. Hake (1957) notes that with eye-fixation the ability to accurately locate a spot of light in the visual field has been shown to depend only on the radial position of the light. Localization accuracy is thus independent of detection variables such as intensity, contrast and duration given that the light is detected. The accuracy of immediate localization decreases as the projected light is moved away from the center of the visual field and is best along the horizontal and vertical axes of the visual field. Thus, as long as a change of state in an indicator light is detected, localization will automatically follow, its accuracy dependent only on radial location. The meaning of the detected and located change of state is dependent upon the legend associated with the detected and located indicator.

The psychophysical correlates of EL illumination are largely unknown; therefore, it would be useful to study the detectability of EL light patches even if the design of specific indicator lights was not the goal. For example, what is the degree of trade-off between contrast, intensity, viewing duration, and area of illumination for foveal vision? And how do these trade-offs operate for various degrees of peripheral vision? The peripheral detection of signals becomes important when one considers an array of displays, some of which must necessarily be located near the edges of the visual fields.

New Static Displays. Because EL displays permit great flexibility, an interesting alternative to alphanumeric legend lights is a system of geometric symbols as legends or a combination of geometric symbols and alphanumerics. In a visual search task the search time should be shorter for locating a distinctive geometric form than for locating a specific alphanumeric legend, and search time for certain geometric symbols should be shorter than for others. Displays might be grouped by legends of geometric forms with alphanumerics encased within the forms to distinguish specific displays within a group characterized by a certain form. Suppose, for example, that all displays giving data on life-support systems were indicated by an alphanumeric legend surrounded by an outline equilateral triangle and displays for engine data were indicated by an alphanumeric legend surrounded by an outline rectangle. Eriksen and Hake (1955) show that "extraneous" variables that are correlated with stimuli to be perceived aid in the identification of those stimuli. A set of common geometric forms could be studied to determine which forms are most rapidly distinguished from each other, and if these forms in combination with alphanumeric legends decreased search time as compared to alphanumeric legends alone. The analysis of total information from the display complex into "between" and "within" components could be done as described previously. The manipulation of "between" and "within" information components should produce some mix that would minimize search time. Grouping by spatial location would also be a possible coding technique. The complete replacement of alphanumeric legends by geometric symbols might result in faster search time. An extensive list of such symbols has been presented by Honigfeld (1964). These and other pictorial symbols could be experimentally compared with alphanumerics alone.

As mentioned earlier, the use of EL to construct separate indicator and warning lights seems a waste of the EL technique. Rather than have a legend indicating some particular system and a separate indicator light to describe the state of that system, the two could be combined. For example, the legend itself could be the indicator by showing a change in brightness to describe a change in a state of a system. Warning signals, likewise, could be combined with legend lights or with some part of another display. Legend lights could also change brightness or flash as an attention-getting device when a critical condition existed in a system. If a scale indicator were associated with a system, the pointer or some other part of the display could change in brightness or begin flashing. To implement such instrumentation, a study could be done on the detectability of such warning signals. If an alphanumeric legend were to change state as an attention-getting device, the detectability of such a change would be a function of the number of

characters (total light output) in the legend. The legend would presumably already be bright enough for rapid readability so that the warning signal would have to be a readily detectable increment in brightness or a change from a constant to a flashing state.

DYNAMIC DISPLAYS

Discrete change displays. Two types of conventional display that exhibit discrete changes of state are (1) direct-reading, snap-action counters and (2) displays that exhibit blocks of alphanumeric material in sequence similar to a snap-action counter. For want of a generic term for the latter class of displays, they are referred to here as "printers" although no actual printing operation is involved. Consider an hypothetical on-board computer in a spacecraft that has a display indicating its current operational phase. The display might first show "READ-IN", then snap to "COMPUTE" and then to "READ-OUT". The EL counterparts of counters and printers are easily constructed with no moving cylinders or tapes required to display the information. A simple process of activating and deactivating segmented electrodes will present all the possible alphanumerics for which the counter or printer has been designed.

The perceptual task involved in the monitoring of counters and printers is absolute identification, which, as noted before, presupposes detection and discrimination. Since EL counters and printers involve many of the same psychological variables as legend lights, these variables are not rediscussed here.

A new variable, the rate of information presentation, appears in the study of snap-action displays and their EL counterpart. Garner (1962) has discussed the information theory measure of channel capacity, in bits, for human information processing. This measure provides a fruitful approach to the problem of optimum and maximum allowable information presentation rates for EL counters and printers. As mentioned earlier in the discussion of legend lights, the information components of a display complex are directly analogous to the components of variance in an analysis of variance design (see Garner, 1962). Any or all of the information components may be involved in changes of state over time. Thus, the rate of information transmission in bits per unit time can be computed for the appropriate information components.

If identification performance and response latencies for a display were related to presentation rate in bits of information per unit time, one could find the perceptual channel capacity for that display and perhaps an optimum presentation rate. One might, of course, measure performance simply as a function of the number of changes of state per unit time in a chosen display and, thus, find the optimum and maximum rates. However, the advantage of measuring performance as a function of bits of information per unit time is that this measure is potentially generalizable to all displays of a given type. This research might promote the understanding of counters and printers in general rather than only the specific display under consideration.

The effect of sequential dependencies in counter and printer displays is of special interest in an analysis of information transmission rates. Consider, for example, a counter that is displaying the sequence of integers 01, 02, 03, 04, ... at a given rate. If an observer knows the design characteristics of the counter and is looking at it at a

given point in time (t) and sees 03 displayed, then he can be certain that at t+1 it will display 04. Thus, no information is transmitted by the change from 03 to 04: if the observer is to report the sequence of integers presented, he can correctly report this sequence by remembering only the integer seen at time t. At the other extreme is a display with a fixed number of alternatives to be presented, and each alternative is equally likely to occur on any change of state. This display is transmitting the maximum information. Between the two extremes of the zero-transmission display and the maximum-transmission displays are displays exhibiting various degrees of sequential dependency. These dependencies reduce from the maximum the amount of information transmitted. Hyman (1953) shows that reaction time to a display is a linear function of information transmitted and that the function for displays with internal dependencies is identical to that for displays without internal dependencies. That is, reaction time is a linear function of information load no matter how that load is generated.

If this is true for EL counters and printers, then displays that exhibit sequential dependencies can carry more possible alternatives, since the dependencies reduce information content and amount of decrease can be compensated for by increasing the number of alternatives. Consider two counters: one counter may exhibit any one of N (equally likely) integers; the other counter may exhibit only integers that are greater than the last integer exhibited, although it has N integers possible. If each counter is to be run at the same rate, then N + X integers may be programmed for the unidirectional counter where the additional X integers add as much information as was lost by restricting the counter to "upward" motion only. Alternatively the unidirectional counter with N integers could be run at a faster rate (within the limits of human channel capacity) than the nondirectional counter with N integers, since perceptual performance should be a function only of information transmitted per unit time. These deductions from Hyman's work are speculative and should be verified with EL displays.

There are practical considerations that cannot be overlooked when considering optimal transmission rates for different types of counters and printers. For example, consider a printer that must sequentially transmit a fixed amount of information to a human monitor, and all the information to be transmitted is already available to the printer. For this display the goal of the design engineer must be to maximize the transmission rate while keeping the readability at an acceptable level. That is, he may manipulate the transmission rate within the limits of human channel capacity. On the other hand, consider a "real-time" counter or printer that displays information about a continually changing state of affairs such as altitude or air-speed. The transmission rate is now out of the designer's control to a certain extent. The only way that he can control the presentation rate is to determine the upper limit of the rate of change in the variable whose values are to be displayed, and choose a scale unit for the display such that, at this upper limit, the transmission rate will be less than the channel capacity of the observer. An altimeter, for example, might be designed with an EL counter giving readings in thousands of feet with an auxiliary dial display giving readings in hundreds of feet. Thus, when the craft was ascending or descending the counter would not be changing readings so fast that the operator could not identify them.

Intuitively, a direct-reading EL counter would seem to have an advantage over a dial display (which also has an EL counterpart) for gross check-reading purposes because no "within display" search is required with a direct-reading counter. This intuitive judgment should be verified by comparing reaction times for EL dial displays vs EL counter displays, each of whose readability has been maximized.

The printer type of EL display would generally not be used to monitor a variable whose states are changing quite often and for which a large number of possible states exist since the information load would be too great in this case. The typical use for a printer display would be to indicate which one of three or four different possible states is present, with each state being in evidence for a relatively long period of time. The "state of operation" display for an on-board computer as given above is an example. A display indicating which phase of a pattern of aircraft landing operations should be currently executed by a pilot is another. For such displays, the rate of change is so slow as to be an unimportant variable.

The greatest possibility for new EL discrete change displays seems to be the use of alphanumeric printers which show either change of state in a physical system or instruct the operator that he should initiate an action. The displays cited as examples in the previous paragraphs are of this type. The imagination of the design engineer can be used here. The psychophysical variables for these new displays are the same as for alphanumeric legends, with the addition of transmission rate as a variable when rapid changes of state are involved.

Continuous change displays. The conventional continuous change instruments for which EL counterparts can be made are the various types of meter and dial displays that have a fixed scale and a moving pointer. Fixed-pointer, moving-scale displays are generally inferior to these (Baker & Grether, 1954), and their EL counterpart would not be easy to build. For these reasons this latter category of displays will be ignored here.

A solid-state analog of a conventional moving-pointer, fixed-scale indicator can be made by properly patterning the electrodes in an EL display. Each of a finite number of possible pointer locations is represented by a thin electrode or electrodes which, when activated, provide a line of EL light that serves as a pointer. By successively activating and deactivating these pointer electrodes, an illusion of a pointer moving continuously along a scale can be produced. Both curved and straight-scale displays can be made in this manner.

The perceptual task required of an operator reading an EL dial or meter display is usually that of identification which again presumes discrimination and detection. The psychological variables involved in the design of these displays are the same as those in the design of conventional meters and dials, with some variations. Baker and Grether (1954) have listed the important variables for the design of conventional dial and meter displays. They give the optimal specifications for such variables as scale unit, pointer thickness, pointer length, location of the scale origin, etc. It may be that the optimal specifications for these variables are the same for EL dial displays. However, since EL dial and meter displays cannot be identical in all respects to conventional displays, these variables need to be investigated using EL displays. The interaction of these variables is also an important consideration.

Another class of EL continuous-change displays is X-Y and polar coordinate plotters. The construction of these displays is described in Section II. The perceptual task for this class of displays may be that of identification, recognition or judgment depending upon the display. Consider an X-Y plotter that plots the altitude of a missile on the Y axis as a function of its distance from the launch-pad on the X axis. This display requires only that the observer identify the X-Y coordinates at any point in time. That is, he must correctly read the altitude and distance values.

Consider, also, an observer who is monitoring a polar coordinate display which is displaying radar information. He has the task of recognition: are the displayed forms representative of airplanes or missiles or hills? He must compare the present stimuli with his recall of previously-seen stimuli. This type of display is not technically feasible with EL alone; however, EL image-intensifiers (Winslow & Kazan, 1963) could be used in conjunction with conventional radar-scopes to form an EL radar-scope.

As an example of a judgment task, consider an X-Y plotter in an orbiting spacecraft that shows as a spot of EL light the location of the spacecraft in a two-dimensional coordinate system representing the latitude and longitude of the craft on the orbited body. If an astronaut were to use this display as an aid to making a maneuver, his perceptual task would involve judgments of the velocity with which the spot of light was approaching a predesignated pair of coordinates, the appropriateness of the course being displayed, etc.

Thus, the perceptual task required in reading a plotter depends upon the kind of plotter in question.

Two major interacting variables in the design of such plotters are the size of the scale unit and the rate of information transmission. The problem is similar to that of designing an EL counter that monitors a physical system. If the physical system being represented on a plotter is changing rapidly with respect to the variables represented by the X and Y axes of the plotter, then an appropriate scale unit for these axes has to be chosen so as to keep the rate of movement of the point of light within interpretable limits.

For human factors research on plotters information theory again seems to be an appropriate tool. If the task required is that of identification, then the rate of change of the point on the plotter must allow the viewer to correctly identify the coordinates of each successive location of the light spot. Thus, information transmitted per unit time is again the basic variable and all that was said previously about sequential dependencies within displays applies here as well: less information is being transmitted by a plotter that the operator knows must transmit a monotonic function over time than by a plotter that may transmit either nonmonotonic or monotonic functions over time. It is probable that with plotters, as with counters, the rate of presentation could be traded for an increase in information in the form of smaller scale units or decreased sequential dependencies.

New continuous-change displays. The possible design characteristics for new continuous-change displays are virtually unlimited. As a result, any new display could

conceivably involve almost any known variable in visual perception and probably some that are unknown. Thus, it is difficult to abstract the specific human factors important to this class of displays. There exist, however, a few new continuous-change EL displays that might suggest the direction the the design of displays might take in the future. One is a simple EL bar graph or histogram in which the bars can continuously change length. Another makes use of the psychological phenomenon of apparent motion in which the successive activation and deactivation of a sequence of light sources produces a "theater marquee effect" of motion along a row of lights. Still another schematically represents on an EL panel the more important changing aspects of the immediate environment of the vehicle carrying the display. These displays form the focal point of the discussion of human factors in new continuous-change displays.

In Section II the design characteristics of an EL bar-graph display were described. One obvious use for a display of this type is to use a single bar of EL light that can be lengthened or shortened to indicate the amount of fuel, or water or oxygen, etc., remaining in storage. If the display had a scale along the side of the bar, one would first study the characteristics relevant to perception of various alphanumeric sizes, shapes, and spacings along this scale along with various scale units. This type of research is the same as that described in more detail in the discussion of legend lights in Section IV. Interacting with the scale characteristics will be the length and width of the bar, the length to width ratio of the bar, the shape of the bar, and the width of the electrodes that produce changes in the length of the bar. Once an optimal set of values is found for this collection of variables, an observer's performance using this display can be compared to his performance using an EL dial display showing the same information in its optimal way. (Dial displays have been traditionally used to convey the same type of information suggested here for bar-graph displays). By "optimal" is meant that design which produces an acceptable percentage of correct identifications with the fastest reaction time.

Now consider a group of physical systems that change their characteristics fairly slowly and that either interact with one another physically or possess relative characteristics of interest to the observer whether or not there is physical interaction. A multiple bar-graph of these interacting variables would show not only the absolute values of each variable but also their relative status. The production of water by the power cells in Gemini 5 is a good example. The amount of water produced, the level of power output, and the relative status of these two variables were of concern to the astronauts, since an excess of water production could affect power output.

In observing a multiple bar-graph showing relative status there are two types of perceptual tasks: (1) identification of absolute values when they are needed, and (2) judgment of relative values and their rate of change. For the identification task, the variables are the same as those for a single-bar display. For determining the optimum display characteristics for judgments of relative values, the number of bars and their absolute and relative lengths and widths would probably be a factor. But the research would have to be geared to the particular display to be used to monitor particular systems, because the meaning of various relative levels of the variables is the important factor. The degree of exactness required in the relative judgment will vary with this meaning.

The second display prototype to be discussed is a display that makes use of the illusion of movement caused by successive activation and deactivation of a sequence of EL electrodes. An example of an EL display that employs apparent motion is shown schematically in Figure 6. It is a spacecraft body rate indicator developed by Autonetics Division of North American Aviation, Inc., and is described by J. S. Frost (1965) as follows:

> "The vertical arms indicate the rate of change of pitch, while the horizontal arms indicate roll. Yaw is shown by the outer sectors. The circular area in the center of the display indicates power is available to the system.
>
> A slow change in attitude will be a sequential illumination of segments in the appropriate direction. As rate increases, the speed of 'segment travel' will also increase. In the limit, persistence of vision will show all segments in a particular arm illuminated. At that point, the display is so programmed to flash the entire arm; the flash indicating rate of attitude change in excess of maximum allowable."

In order to establish general design specifications for the production of good apparent motion in EL displays like the one in Figure 6 a parametric study of apparent motion needs to be done. No study of all the relevant variables and their interactions exists in the literature on apparent motion. The variables most often studied have been the flash and interflash interval between lights that are alternately flashing (Brown & Voth, 1936) and the distance between the flashing lights (Obonai & Suzumura, 1954). A complete study of this phenomenon using EL light sources would include 25 variables, (1) the number of lights, (2) the intensity and/or contrast of lights, (3) the spacing of lights, (4) interflash interval, (5) flash duration, (6) the ratio of flash duration to interflash interval, (7) the shape of the lights, and (8) the presence or absence of eye fixation. All these variables would probably interact making this a very heroic but also a very worthwhile study. Apparent motion is a compelling phenomenon and may be a good attention-getting device in addition to giving information about the state of a system.

The use of illusions other than apparent motion is an interesting possibility for EL display design. There are hundreds of visual illusions on record and a search of the literature may produce some illusion that could be ingeniously used in EL display design; e. g. "Reversible Figures" might be used with differential lighting producing the reversal. One other illusion which is not of the geometric variety has indeed been used in EL display design: J. S. Frost (1965) produced subjective color (the Land Effect) in an EL display by alternating the frequency of the driving current so that the phosphor alternately gave off green and then yellow light. When the alternation between frequencies was 40 cps areas of different intensity in the display were seen as different colors. When perfected, this ingenious technique might solve the problem of the limitation of the colors available in EL phosphors.

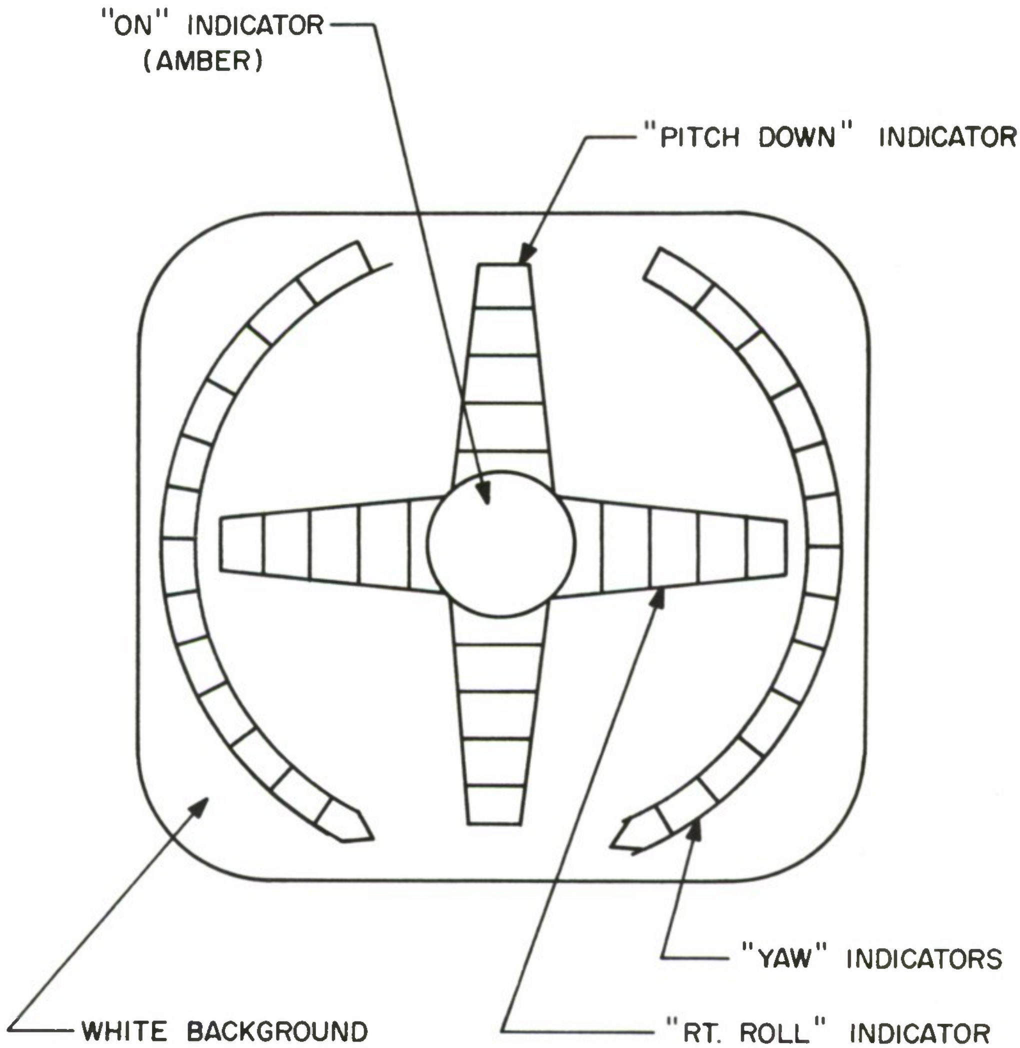

Figure 6. Spacecraft Body Rate Indicator (Courtesy of North American Aviation Co.).

The final display type to be discussed schematically represents on an EL display the more important changing aspects of the environment of the vehicle carrying the display. It, also, was designed by Autonetics and reported by Frost (1965). It is called a Rudimentary Vehicular Status Display and is shown in four of its many possible states in Figure 7. It is designed to maintain orientation and to summarize dynamic position information in a submarine. Frost's description of the display design is as follows:

> "The upper horizontal lines represent the surface, and their successive illumination will give the operator a qualitative picture of the depth of the ship. Sea bottom is depicted in similar fashion by the wedges at the lower right and left hand corners of the display. The triangular shapes in the center of the presentations indicate dive or surfacing condition; the rate of flashing of the appropriate triangle serves to indicate rate of rise or fall, and is coordinated with surface and bottom indication.
>
> The triangular and trapezoidal shapes at the lower center form typical 'runway' indicators indicating right or left rudder, and rate of traverse along the chosen pathway. This latter effect is simulated by sequentially extinguishing segments along the runway, the rate of segment travel indicating forward speed. In each case the display serves to provide a qualitative indication of rate, acceleration, position, and attitude, and may be supplemented by more precise data from other instruments."

Apparent motion is used here in combination with a complex, continually changing geometric pattern. The psychological variables involved in the perception of this display are numerous and quite complex. In the study of human factors involved in a display embodying this degree of complexity, it would be practical to compare the perceptual performance resulting from the display with that resulting from conventional displays or display complexes designed for the same purpose. The display that both produced the best perceptual performance and was the most compatible with good engineering principles could then be chosen. More detailed research on such displays would require a major research effort in the area of pattern perception. This research program would yield results of interest to both the experimental psychologist and the design engineer. The psychologist would probably find complex EL displays to be a perfect vehicle for the study of patterns and form, while the design engineer would gain a large amount of human factors data from the research program.

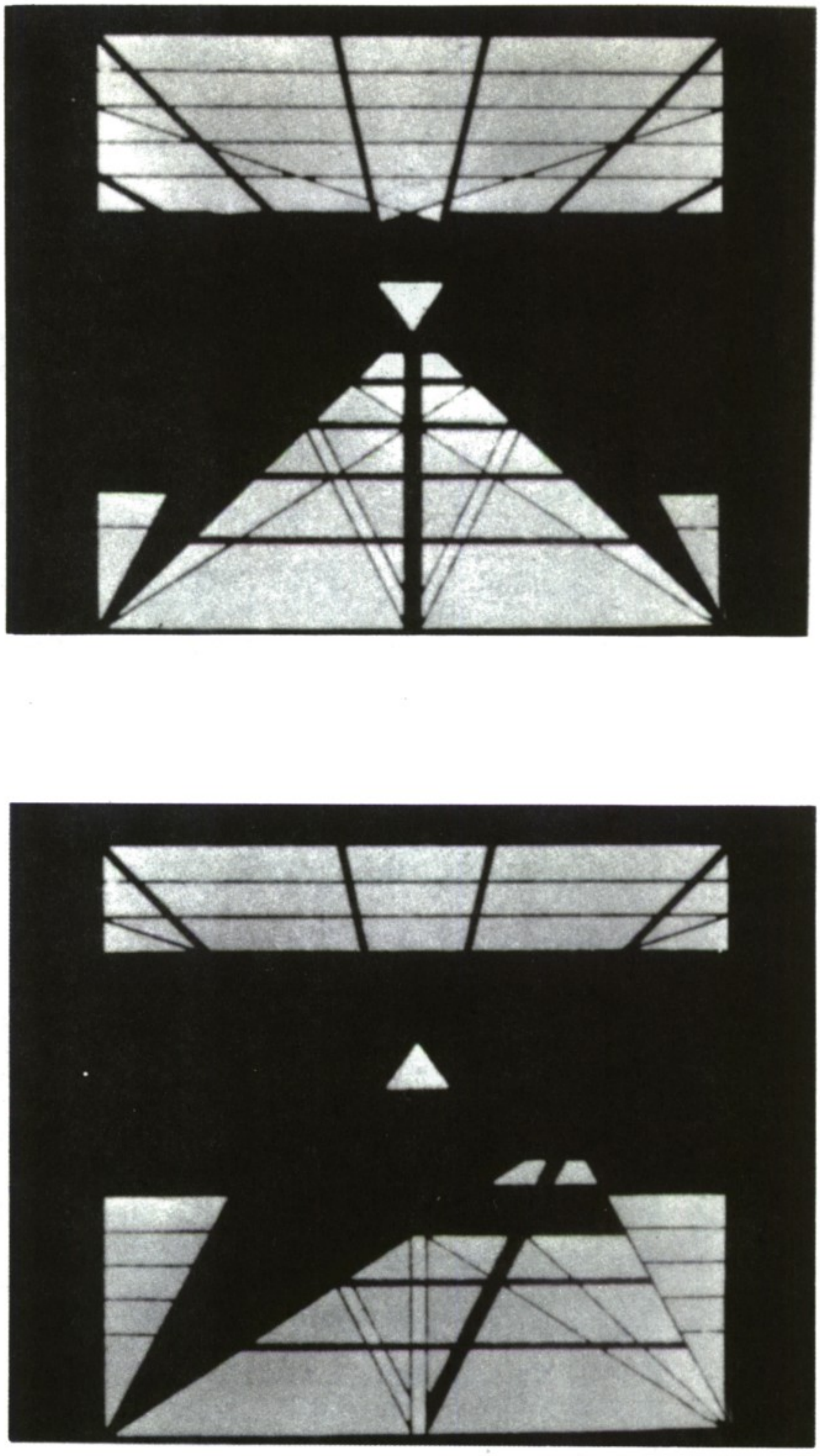

Figure 7. Rudimentary Vehicular Status Display.

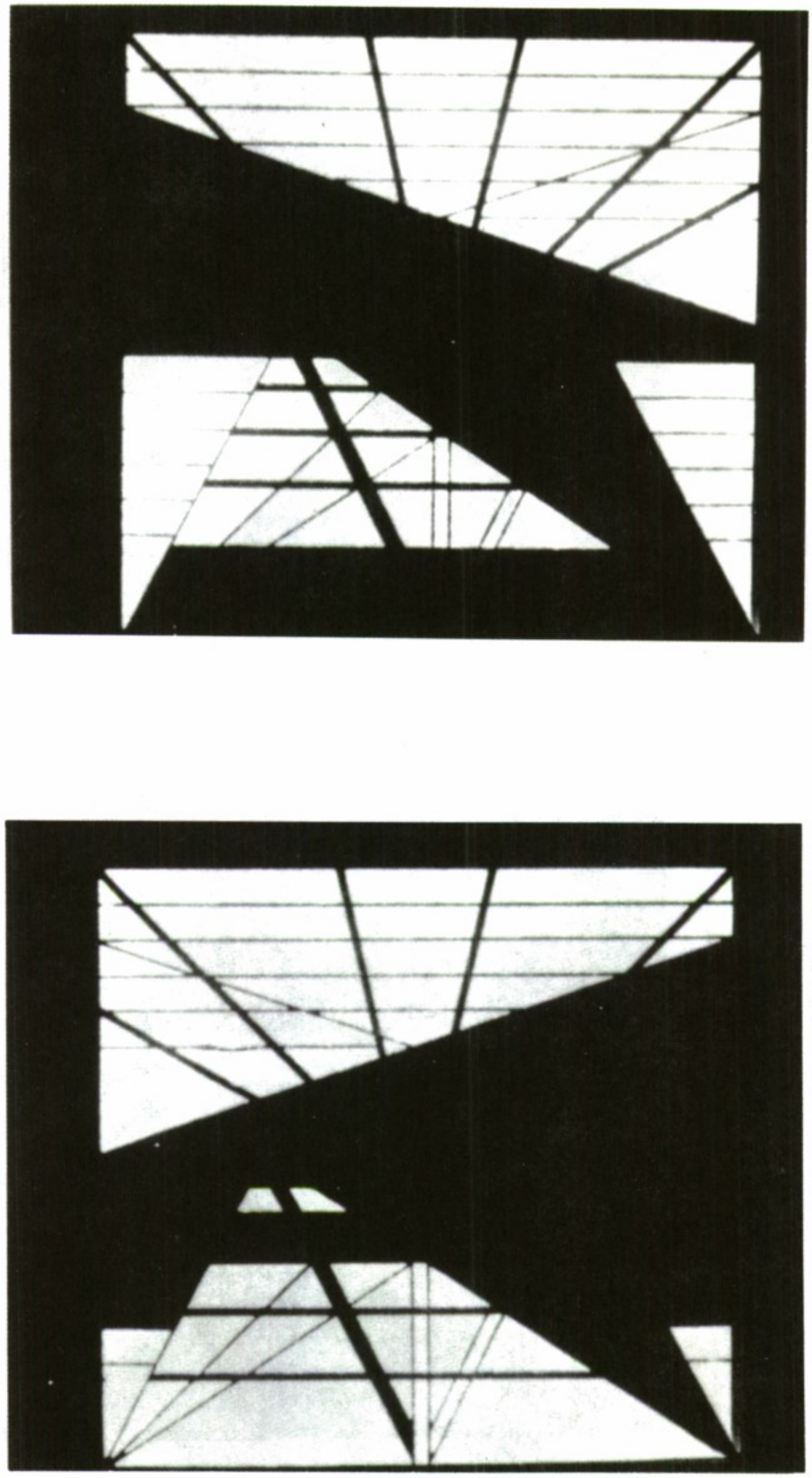

Figure 7 (Concluded). Rudimentary Vehicular Status Display.

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13. ABSTRACT

This report presents an outline of a broad program of psychological research that will provide human engineering standards for the design of electroluminescent (EL) display devices. The physical characteristics of EL lighting are discussed, after which the possible types of EL displays are categorized as discrete or continuous displays, and as dynamic or static displays. Five types of perceptual tasks that might be required of an observer of an EL display are described, and each display category is then discussed in terms of the perceptual task(s) required to monitor the display in question. For each display-task combination, human factor research is proposed and some experiments are laid out in detail. The conventional variables such as intensity, contrast and viewing duration are considered for each display-task category as well as some less familiar variables based on the use of information theory. Examples of existing and proposed EL displays are given in connection with the proposed research.

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